Final Report on AOARD contract FA2386-09-1-4015, "Laser cooling with ultrafast pulse trains"

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Overview

The goal of this contract was to investigate a novel laser-cooling technique that uses femtosecond lasers to extend the range of ultracold atomic species. This contract continued the previous AOARD contract FA4869-08-1-4005 of the same name.

Since the award of this contract, we have made significant advances in construction of the apparatus for laser cooling of hydrogen and in characterization of the hydrogen beam. In particular, we

- achieved 3 kW laser intensity in a test resonator toward laser guiding of hydrogen
- generated multi-Watt ultrafast pulses at 1944 nm toward a cooling laser at 243 nm
- improved our characterization of the hydrogen beam dissociation fraction

On the ion experiment, we have advanced toward proof-of-principle of the laser cooling technique by

- improving our ion fluorescence signal by an order of magnitude
- rebuilding the linear ion trap used for two-photon spectroscopy

Hydrogen experiment

Optical resonator for atomic beam guiding

The scheme for laser cooling of hydrogen requires transverse optical guiding of the H beam to increase the interaction time of the atomic beam with the cooling laser. The optical guide must be operated at a wavelength of 514.65 nm so that Stark shifts of the H level structure do not broaden the cooling transition. The guiding potential requires laser power equivalent to 20 kW at this wavelength, which will be obtained by resonant enhancement of the 2 W laser source constructed under previous AOARD contracts.

In this period we have demonstrated 3 kW circulating power in a test resonator, a significant step toward construction of the optical guide. The test resonator was built using custom mirrors with reflectivity measured at 99.99965% and was mounted in a vacuum chamber held at a few tens of mbar. We measured a resonator finesse of $9.2 \pm 0.2 \times 10^4$ (Fig. 1) and matched the laser transverse mode to the resonator mode at the 99% level. A servo system of the Pound-Drever-Hall type was constructed to actively stabilize

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The goal of this contract was to investigate a novel laser-cooling technique that uses femtosecond lasers to extend the range of ultracold atomic species. During this grant work was performed to significantly advance construction of the apparatus for laser cooling of hydrogen and in characterization of the hydrogen beam. The following were achieved: 1) 3 kW laser intensity in a test resonator toward laser guiding of hydrogen, 2) generated multi-Watt ultrafast pulses at 1944 nm toward a cooling laser at 243 nm, 3) improved characterization of the hydrogen beam dissociation fraction. Additionally, steps toward proof-of-principle ion experiments with the novel laser cooling technique were made by improving the ion fluorescence signal by an order of magnitude and rebuilding the linear ion trap used for two-photon spectroscopy.

15. SUBJECT TERMS

Atomic Physics, Femtosecond laser , Ultra Cooling

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the laser frequency to cavity resonance, but acoustic environmental noise has so far prevented successful stabilization. However, the frequency resonance condition was transiently fulfilled and we observed resonator transmission up to 40 mW, corresponding to 3 kW circulating power. The finesse measurement indicates negligible optical loss in the resonator, so frequency stabilization should enable us to reach circulating power up to 60 kW.

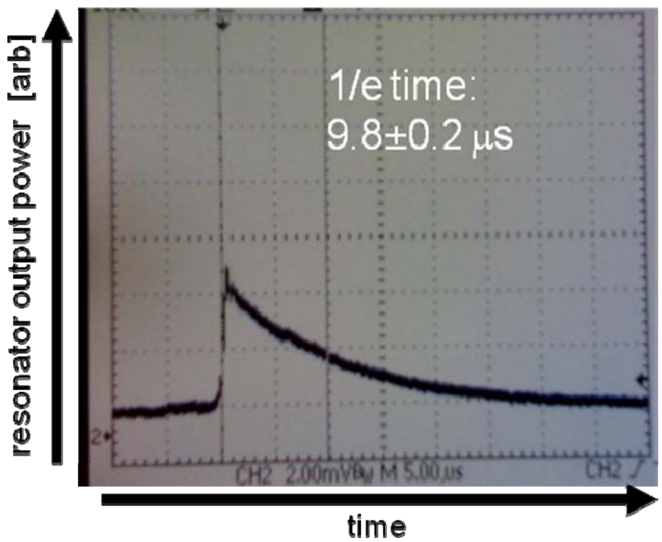

Figure 1. Ringdown measurement of high-finesse resonator. The optical storage time of 9.8±0.2 μs indicates a finesse of $9.2 \pm 0.2 \times 10^4$.

Ultrafast pulses at 1944 nm for laser cooling

The cooling laser for hydrogen is required to produce ultrafast pulses at 243 nm with Watt-level average power at several hundred MHz repetition rate. We will obtain this light by octupling of 1944 nm light in nonlinear crystals. While this method will yield the highest average power, the seed pulses at 1944 nm are nontrivial to generate. Under our previous contract, we demonstrated generation of ultrafast pulses in the 1 μm band by spectral slicing of an octave-spanning supercontinuum produced using telecom fiber optics. This work has now appeared in Optics Express (#2 in publication list) and has also been presented at a conference (#3 in publication list).

In this period, we investigated the generation of high-power 1944 nm pulses by supercontinuum slicing. We increased the repetition rate of the supercontinuum source to 300 MHz using a harmonically mode-locked fiber laser as the supercontinuum seed. This laser generated substantially longer pulses than the previous 40 MHz laser, but external soliton compression gave sufficiently short pulses for efficient supercontinuum generation. We amplified the 1944 nm band of the supercontinuum using a thulium fiber preamplifier and subsequent thulium fiber, obtaining 10 W of average power for future upconversion to 243 nm.

Characterization of dissociation fraction in the H beam

The H beam source operates by dissociation of molecular hydrogen in an RF discharge. Since laser cooling will only be effective on H atoms, we need to characterize the fraction of H_2 molecules that are successfully dissociated. In the last period, we estimated the dissociation fraction at approximately 50% using emission spectroscopy of the discharge source with a spectrograph of 2 nm resolution. We have now improved our resolution to 0.2 nm using a double monochromator, enabling us to resolve the individual rovibrational emission lines from the residual H_2. These measurements (Fig. 1) allow us to definitely state that the atomic beam contains 80±10% H atoms by number.

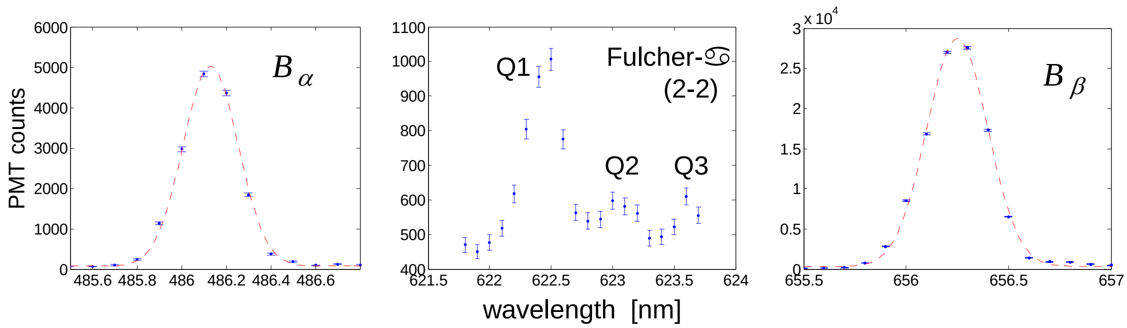

Figure 2. High-resolution emission spectroscopy of the hydrogen discharge source.

Ion experiment

To investigate our two-photon cooling scheme [Ki06], we have been attempting to perform spectroscopy on the nonresonant $S_{1/2} – D_{3/2}$ two-photon transition of trapped Yb^+ ions with a high-repetition-rate mode-locked laser constructed under previous AFOSR contracts. In the previous period, we searched for the two-photon transition and obtained promising signals with narrow linewidths using a fluorescence depletion technique. However, the signal-to-noise of these measurements was too low for definite claims to be made and the ion trap was generally rather unstable. In this period, we undertook improvements to the apparatus in aid of future measurements.

Order-of-magnitude improvement in ion fluorescence signal

The fluorescence depletion spectroscopy used to search for the two-photon transition has an inherent sensitivity limit due to the level structure of Yb^+. After approximately 200 photon scattering events on the 370 nm detection transition, the ion falls into the same $D_{3/2}$ state that is the target of the two-photon transition, so that the ion fluorescence is low whether or not the two-photon transition was excited. Hence the detection period can only last for about 200 scattering events before the experiment must be repeated. In our previous setup, the fluorescence detection efficiency was about 10^{-3}, a typical value for ion traps. We have developed a novel detection system based on a microfabricated phase Fresnel lens (Fig. 3) that raises this efficiency to 1%. The detection system was successfully tested in a new trapping apparatus constructed with funding from the Australian Research Council. These results have been submitted for publication (#1 in publication list) and has also been presented at several conferences (#4 and #6 in publication list).

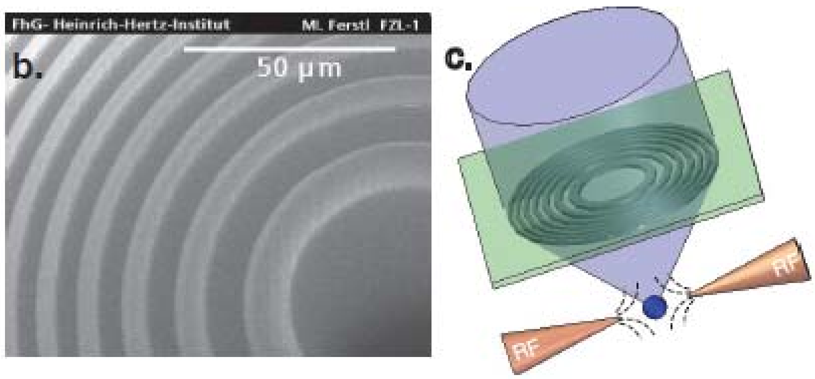

Figure 3. High-efficiency detection of ion fluorescence with a microfabricated phase Fresnel lens. Left: scanning electron micrograph of Fresnel lens showing etching of phase profile in lens surface. Right: schematic of the test apparatus. Ions are trapped in the RF quadrupole field of two needle electrodes and ion fluorescence is collected and collimated by the Fresnel lens.

Rebuild of linear ion trap

The ion crystals used in these experiments are held in a linear RF trap with a long aspect ratio. In this trap design, the RF fields are purely transverse to the long axis and the confinement along the axis is purely electrostatic, enabling the crystallization of long strings of ions that are optimally matched to the focal volume of the mode-locked laser light. However, the electrode structure of the trap was observed to create significant RF fields along the trap axis, so that only strings of a few ions could be crystallized for long periods of time. Finite-element simulations showed that the bending of the RF field lines onto the axial confinement electrodes was responsible for this problem.

In this period, we rebuilt the trap electrode structure with new axial electrodes to eliminate the field line bending. At the same time, we incorporated several new electrodes into the vacuum chamber for cancellation of stray electric fields, as such stray fields can also affect crystallization. Surface contamination of vacuum components affected the vacuum systems for both ion traps during this period and prevented experiments with the rebuilt trap. The contamination was traced to a bad batch of cleaning solvent. Recleaning with new solvent successfully removed the contamination in the new trap vacuum system, so we expect to recover the rebuilt trap vacuum in the near future by the same procedure.

Journal publications relating to this contract:

1. "Imaging trapped ions with a microfabricated lens for quantum information processing," EW Streed, BG Norton, A Jechow, TJ Weinhold, and D Kielpinski, submitted (arXiv:1006.4192v1)

2. "Mode-locked picosecond pulse generation from an octave-spanning supercontinuum," D Kielpinski, MG Pullen, J Canning, M Stevenson, PS Westbrook, and KS Feder, *Opt Express* **17**, 20833 (2009).

Conference presentations relating to this contract:

3. "Mode-locked picosecond pulse generation from an octave-spanning supercontinuum," D. Kielpinski, M.G. Pullen, J. Canning, M. Stevenson, P.S. Westbrook, and K.S. Feder, Australian Conference on Optical Fibre Technology, Adelaide, 29 Nov – 3 Dec 2009

4. "Large-scale quantum computing with phase Fresnel lenses," EW Streed, BG Norton, JJ Chapman, and D Kielpinski, Australasian Conference on Optics, Lasers, and Spectroscopy, Adelaide, 29 Nov – 3 Dec 2009

5. "Optogalvanic Spectroscopy of the 2F7/2-1D[5/2]5/2 Repumper Transition for Yb+ Optical Frequency Standards," MJ Petrasiunas, EW Streed, TJ Weinhold, BG Norton, WM Itano, and D Kielpinski, Australasian Conference on Optics, Lasers, and Spectroscopy, Adelaide, 29 Nov – 3 Dec 2009

6. "Optical Characterization Of A Phase Fresnel Lens For Trapped Ion Quantum Computing," BG Norton, EW Streed, JJ Chapman, and D Kielpinski, Australasian Conference on Optics, Lasers, and Spectroscopy, Adelaide, 29 Nov – 3 Dec 2009

7. **Invited:** "Investigation of atomic collisions in time scales varying from microseconds to femtoseconds," R.D. Glover, M. Pullen, D.E. Laban, K.J. Matherson, W. Wallace, G.F. Hanne, D. Kielpinski, and R.T. Sang, International Symposium on (e,2e), Double Photoionization and Related Topics, Lexington KY, 30 Jul – 1 Aug 2009

8. "Absolute laser frequency stabilisation to ions in a discharge," EW Streed, TJ Weinhold, and D Kielpinski, 19th International Conference on Laser Spectroscopy, Hokkaido, Japan, 7 – 13 Jun 2009